NASA TECHNICAL NOTE

NASA TN D-2176

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NASA TN D-2176

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1964

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SUMMARY

Lack of a suitable device for simulating the lunar gravity is considered to be the cause for the current lack of information on the ability of the lunar explorers to perform various self-locomotive tasks, such as walking, running, and jumping. Basic considerations reveal the need for a lunar-gravity simulator which provides essentially unlimited duration of the test condition and space limitations from at least 10 to 12 feet vertically and as much as 150 feet or more horizontally. On the basis of these needs, a new type of gravity-simulation technique was developed, and some tests were made to evaluate the suitability of the technique by using a preliminary setup. The results of these tests indicated that the technique was useful and that man will be able to walk and run on the moon but will have difficulty in changing his position rapidly. In addition, he should be able to jump vertical distances from 12 to 14 feet when unencumbered with a spacesuit or equipment and should most likely not sustain injury in falls from these distances; he should have little difficulty in climbing stairs, ladders, and poles. A motion-picture film supplement is made available to illustrate some of the results of these tests.

INTRODUCTION

After the initial successful lunar landing of the Apollo lunar excursion module, the astronauts are expected to leave their vehicle to make scientific measurements, to explore the lunar features such as the craters and possible caves, to inspect their vehicle, and to prepare it for the return trip. Subsequent missions will very likely require the astronauts to erect lunar bases with permanent housing facilities. Because the lunar environment is considerably different from that of the earth, the explorers undoubtedly will have to adjust their accustomed methods of self-locomotion - that is, their ability to walk, run, jump, and perform other body movements under various working conditions - in order to accomplish the mission objectives. Based on current knowledge of the lunar environment, there are essentially two conditions to which the lunar explorers will have to adjust. The first condition is that of the low gravitational field which is approximately one-sixth that of the earth. The second condition is that of having to wear bulky and cumbersome spacesuits whenever venturing out of the spacecraft or lunar base because of the lack of an atmosphere and the need for protection from the lunar temperatures and possible micrometeor and solar radiation showers.

Inasmuch as the success of the lunar missions and the safety of the personnel will depend at times on the self-reliance of the explorers for extended periods of time and, perhaps, over considerable distances, extensive knowledge of the effects of the lunar environment on the physical capabilities of man should be made available prior to the planning and execution of the mission. A review of the current literature reveals only a limited amount of information at hand and only a relatively small research effort in progress that deals specifically with the mechanics of self-locomotion as affected by these conditions. One reason for this dearth of information appears to be the lack of a method that simulates the reduced lunar gravity for extended periods of time and permits the test subjects to move about freely over considerable distances. Consequently, a study was undertaken at the Langley Research Center to develop a practical lunar-gravity-simulation technique that would be directly applicable to the locomotive studies of man. The preliminary results of this study are presented in this report, and, even though emphasis was placed on the lunar condition, these results and the technique that was developed are considered to be also directly applicable to problems relating to the design of rotating space stations.

SYMBOLS

G	simulated gravity
G_{av}	average value of simulated gravity
ΔG	incremental change in simulated gravity
g	gravity acceleration at surface of earth
g_{peak}	peak acceleration during vertical jump of subject, g units
h	approximate distance between subject's center of gravity and soles of his feet, ft
h_w	displacement of walkway, ft
Δh	displacement of subject from walkway during jump, ft
Δh_{corr}	corrected height corresponding to constant gravity, ft
L	length of suspension cable, ft
m	mass
N	ratio of desired simulated gravity to earth gravity, G/g
ΔN	ratio of incremental change in simulated gravity to earth gravity, $\Delta G/g$
R	radius of curvature of trajectory

V	velocity
W	weight
θ	inclination angle between suspension cable and the vertical
$\Delta\theta$	incremental change in inclination angle between cable and the vertical

BASIC CONSIDERATIONS FOR LUNAR-GRAVITY-SIMULATION TECHNIQUES

There are several factors to be considered in the selection and development of a practical technique for studying the locomotion of test subjects under simulated lunar conditions. Among these factors are the modes of locomotion that will be employed by the explorer in performing various tasks, the physical characteristics and condition of the explorers, the type of garb and the equipment or load that he wears or carries, and the type of surface over which the explorer is attempting to perform a given task.

Modes of Self-Locomotion

The modes of self-locomotion can be categorized into essentially three specific types, namely, self-transportation, load handling, and manipulation of mechanical devices. The first of these types, self-transportation, consists primarily of walking, running, jumping or leaping, crawling, and climbing. Within the confines of the lunar base, the lunar explorers are concerned with movement with ease from room to room and from one level to another. Of interest in this situation is the use of stairs, ladders, handgrips, railings, chutes, sliding poles, and any other devices that will assist the explorers in moving about the base. External to the lunar base, the explorer will perform scouting missions, probably several miles from the base, to observe the lunar features and take scientific measurements. For these missions, the explorer most likely will be carrying various pieces of heavy and bulky equipment or supplies. Methods of assisting the explorers by use of auxiliary devices, such as a rocket jump pack, will be of interest for this situation. Also included in this category is the capability of the explorer to use his arms and legs in breaking a fall to prevent injury to himself and his life-preserving spacesuit.

The second category is involved in the erection and supplying of the lunar bases and in the performance of emergency rescue missions. Here the explorers will be lifting, catching, throwing, pulling, and pushing heavy and bulky loads.

The final category, that of manipulation of mechanical devices, involves the operation of various pieces of vehicular, erection, and scientific equipment and consists of body movements such as pedaling, pumping, prying, hammering, torquing, pushing, and pulling.

Consideration must be given to the special design features of the gravity simulation required for performing tests of these various modes. The mode of self-transportation generally imposes the requirements for space and duration of the testing period. To approximate the vertical distance a person would be capable of reaching in a jump on the moon, assume that this distance would be equal to the ratio of earth gravity to the lunar gravity times the distance the subject is able to reach in the earth gravity. Simple tests have shown that a person is capable of jumping about 20 to 22 inches on earth from a standing position; consequently, provisions should be made in the simulation equipment for at least six times this vertical distance, or at least 10 to 12 feet. Inasmuch as walking and running are to be considered, it probably would be desirable to accommodate horizontal distances of several hundred feet; however, the actual limits for the horizontal distance will undoubtedly be dictated by conditions such as the size of the available room for carrying out the tests. Some indication of a minimum distance is given by assuming that it may require a couple of seconds to accelerate to the maximum running pace and that a minimum time of 4 or 5 seconds at that pace is desirable, followed by a 2-second period to decelerate. Based on an assumed maximum running speed of 20 feet per second, the required distance would be about 150 feet. It is evident, however, that a number of the other body movements can be studied in much less distance, perhaps half to a quarter of this distance.

It would be desirable for the duration or period of the gravity simulation to be sustained for an unlimited time to permit the test subject to perform any of the body movements in a natural and unhurried manner. As with the distance consideration, however, a number of body movements can be studied even if the simulation time was approximately 10 to 20 seconds.

Other features of the simulator that may be required to accommodate the various forms of self-locomotion are steps, ladders, handgrips or railings, poles, or an inclined walkway with an adjustable slope. Provisions should be made for simulating various sizes and shapes of heavy and bulky equipment and for operating different forms of equipment.

Physical Characteristics of the Lunar Explorer

It appears reasonable to assume that the lunar explorers will reach the moon without appreciable deterioration of their physical condition inasmuch as the effects of extended periods of weightlessness or near-weightlessness will have been determined prior to this mission and provisions will have been made for the crew members to carry out adequate conditioning exercises during the translunar flight. Consequently, it does not appear necessary to precondition test subjects to degrade their performance prior to their participation in the locomotion studies. For purposes of a general exploratory study, subjects of all body types should be tested so that the results will have a more general application. Therefore, the only specific requirement for the testing technique dictated by considerations of the physical characteristics of the lunar explorers appears to be that the test equipment is capable of accommodating subjects of various sizes and weights.

Equipment and Garb for the Lunar Explorers

In carrying out the locomotive studies, efforts should be made to duplicate the clothing, footwear, and equipment loads. Conventional clothing, such as a lightweight coverall or flying suit and tennis shoes, should be adequate for the studies of movement within the confines of the lunar base, and dummy boxes of various sizes and weight would be suitable for simulating the equipment and supply loads. A pressurized spacesuit is required for studies of operations outside the lunar base, and it should be possible to conduct tests with a conventional pressurized suit using various differential pressures to simulate suits of various degrees of stiffness.

Type of Surface

Within the lunar base, the surfaces of the rooms most likely will have textures similar to those used here on earth, although the surfaces may be composed of native lunar material. Consequently, the locomotive studies can be conducted by using conventional surfaces for the floor on which the subjects will move. Very little is known at this time about the texture and composition of the lunar surface; therefore, studies of movement across the lunar surface can proceed only on the basis of assumptions. It is the traction force that is of prime consideration in these studies, and the effects of different lunar surfaces can probably be simulated by using different combinations of footwear and surface materials which provide various amounts of friction that, in combination with the weight of the subject on the surface, produces the traction force.

METHODS FOR SIMULATING THE LUNAR GRAVITY

Simulation of the lunar gravity can be achieved by effectively canceling five-sixths of the earth gravitational force by means of vertical forces made to act on the test subject's body. These forces should be distributed over the body in proportion to the weight of the individual body members. There are two schemes used in studies of weightlessness that could possibly be adapted to the condition of lunar gravity. (See ref. 1 for discussion of several such schemes.) One of these schemes, immersion of the test subject in water or some other liquid of proper density to produce the desired buoyant forces, appears to be impractical because of the viscous forces of the liquid that develop as the subject attempts to move about. It is felt that these extra forces would be excessive and cause the results of most tests to be misleading. The second scheme is that of using an airplane flying in a near-Keplerian trajectory to produce centrifugal forces which act in the proper direction as detailed in figure 1. The duration of the trajectory is only about 20 seconds, and the space available in the airplanes currently in use for this purpose permits the test subjects to move only a few feet in any direction.

Another scheme, that of a vertical cable attached to the test subject, as shown in figure 2, is possible if the simplifying assumption is made that the gravity-relieving forces can be applied at the center of gravity of the whole body. The basic problem of this scheme is that of compensating for the movement of the center of gravity of the test subject as he moves the various body members relative to each other as illustrated in figure 3, which is a sketch showing the loci for the center-of-gravity locations for all possible body positions.

Because of the undesirable limitations of each of the methods discussed, it was felt necessary to develop a new technique which would be more suitable. The new technique that was finally developed evolved as the result of the following observations and assumptions. The first observation is that, with the exception of a very slight lateral swaying, the body members translate and rotate essentially in parallel planes in the fore-aft and up-down directions (see fig. 4), as a person walks, runs, jumps, and performs the many other tasks in a normal manner. This observation led to the assumption that if the body members are constrained so that they are free to move only in parallel planes, the test subject should be able to perform a number of tasks in a more or less normal manner in the direction of the planes.

The second observation is that the movement of a body or object that is free to move only in an inclined plane with negligible friction is governed by only the gravitational component in that plane. Consequently, it should be possible to study the movement of a test subject under any reduced-gravity level by building an apparatus that would permit the subject to move freely in one plane and then tilt the apparatus so that this plane is inclined at some angle with respect to the vertical, depending on the gravity level desired. To produce an equivalent of the lunar gravity an angle of about 9.5° from the horizontal would be required, as illustrated in figure 5.

Limitations of this method are that tasks involving out-of-plane or lateral motions, such as walking or running on a curved path, swinging a hammer sideways, or jumping laterally, cannot be studied. However, this method appears to offer the advantages of ease of adjusting gravity level, unlimited duration of continuous testing period, and essentially unlimited space for performing the tasks. With the exception of the Keplerian technique, none of the methods or schemes discussed here produces a simulation of the lunar gravity for the internal organs of the body. This shortcoming, however, does not appear to be a problem for these self-locomotive studies in which emphasis is on the problems of mechanics rather than the physiological and psychological effects. The remaining portion of this report is concerned primarily with the application of the inclined-plane technique for simulating gravity fields less than that of the earth.

DESCRIPTION OF EQUIPMENT FOR LUNAR-GRAVITY SIMULATOR

A sketch of one preliminary design utilizing the inclined-plane technique is shown in figure 6. This design was based on the use of a lightweight metal frame with articulated or jointed arms that supported the test subject from behind in such a manner as not to restrict his freedom of movement in the plane parallel to the floor of a special room. The frame was to be provided with frictionless air-bearing pads which rode smoothly over the mirror-covered floor. The room was to be specially painted and lighted to create the illusion that one wall was the lunar surface (the "ground" wall) and the other three walls and ceiling were the lunar sky; light for the room was to come from light sources in the wall opposite the ground wall. The mirrored floor created the illusion that the test subject was standing practically in the middle of a room with the width twice the height of the actual room. To heighten the illusion of the test subject's standing vertically while actually lying parallel to the floor, a few vertically oriented objects such as posts or rock formations were to be mounted on the ground wall. The entire room was to be tilted to the proper angle in order to achieve the desired gravity component.

This design, though possessing several interesting features, was not pursued because of the considerable amount of effort involved. It appeared advisable to approach the problem a bit more cautiously to verify the technique before going to the trouble and expense of this particular design. Consequently, attention was directed toward a much simpler design that could be easily built and modified as dictated by the exploratory studies. The result of this approach is shown in figure 7, which illustrates the cable-suspension system that evolved. The test subject is supported in the nearly horizontal attitude by a series of parallel 1/8-inch-diameter steel cables attached to various parts of the subject's body and to an overhead trolley-and-track system by means of a short single cable and crossbar. The lengths of the various cables are adjusted so that the test subject can stand with a normal erect posture on an inclined walkway which is parallel to the track. The use of the multiple cables permits the body members to move freely in essentially parallel planes. The cables are made as long as possible to minimize the slight out-of-plane movement that is generated as the cables pivot about the fixed attachment points at the crossbar. The trolley-and-track system permits the whole suspension system to be moved by a test operator so that the cables remain directly overhead as the subject moves back and forth, thereby eliminating any fore-and-aft drag of the cables on the subject.

Inclination of the test subject is established by displacing the walkway from directly beneath the track. The displacement of this walkway as a function of the magnitude of the simulated gravity in terms of the gravity ratio, that is, the ratio of simulated gravity G to earth gravity g for different suspension cable lengths, is shown in figure 8. Also shown in this figure is the variation of the gravity gradient in terms of change in gravity ratio per foot elevation with the length of the suspension cables. This gradient, which is experienced by the test subject as he jumps from the surface of the walkway or changes his "apparent" elevation by climbing steps or a slope, is produced by the changing angle of the suspension cable whose attachment point is fixed in the one direction. When cable lengths of 50 feet or greater are used, the gravity gradient can be held to a value of 0.02 or less. This value appears to be reasonable for some applications. The equations for the walkway displacement and gravity gradient are given in appendix A.

A preliminary setup of this equipment was made by using ropes and canvas slings, as shown in figure 9, to determine the optimum number of support cables and attachment points for the various body members; several different test subjects participated to ascertain a sampling of opinions. On the basis of these opinions, it was felt that support of the body at the head, the chest, the hip and buttocks, and the calf of each leg would be adequate and that the cables would not significantly interfere with the normal body movements. Support of the arms, just below the elbows, was found to be optional depending on the subject's preference and the tasks being performed. Support of the lower leg was particularly troublesome, but the use of a crossbar on which to rest the leg with a separate cable to support each end of the bar proved to be usable for most tasks.

Following the selection of the body suspension points, a somewhat more refined version of the proposed equipment was prepared (see fig. 10); this version used a revised suspension system attached to a small trolley unit mounted on an overhead monorail within the flight hangar at the Langley Research Center. The trolley unit weighed about 10 pounds and was unpowered. About a 40-foot clearance was provided by the track so that the cables had to be made shorter than desired; however, this was not a significant problem for the exploratory work to be done with this equipment. The system proved to be practical, with the exception of the trolley unit which tended to drag on the test subject because of the friction of the trolley wheels on the track as the subject moved back and forth along the walkway. A revised suspension was developed for the lower leg to eliminate the crossbar cable in front of the test subject because it got in his way when he tried to walk or run.

EXPLORATORY GRAVITY-SIMULATION TEST RESULTS

A motion-picture film supplement has been prepared and is available on loan. A request card form and description of the film will be found at the back of this paper.

During the course of working with the two arrangements for the simulator equipment, a number of simple experiments and observations were made concerning the ability of test subjects to perform various body maneuvers under the influence of the reduced gravity. Whenever practical, similar tests were also made under normal earth gravity for purposes of comparison. Most of the tests were made with three subjects who were usually wearing street clothes and shoes, and the surface of the walkway on which they were supported was ordinary unfinished plywood. One of these three subjects was of medium height and husky build, the second was tall and of heavy build, and the third was tall and of light build. Observations and comments noted by the test subjects are discussed in the subsequent paragraphs.

Standing

In general, all subjects appeared to adjust to the test conditions within a minute or two, did not complain of discomfort or unusual sensations while restrained by the equipment, and were not particularly concerned about the restraint of their body movements to the one plane. It was difficult for the test subjects to sense the simulated vertical direction, particularly with the feet placed close together. Very often a subject was observed to stand in a stooped attitude, and there was a tendency for him to develop a stance with one foot slightly ahead of the other in a manner somewhat similar to that used on board a rolling ship. In some cases the subject tended to move back and forth continually as though trying to "feel" for his stance, and often the subjects ended up standing on their tiptoes. These effects are attributed in part to the fact that the pressures on the feet were very low because of the low weight of the body. Since these pressures are normally used by the subject's sensory system, in conjunction with other sensory cues, to detect the vertical direction and loss of balance, the subject apparently unconsciously used either the feet-apart stance to produce a more stable condition or used the fore-and-aft or the raising-to-the-tiptoe movement in an attempt to increase the foot reaction pressures and, consequently, to improve his sensory responses.

One of the other sensory cues used to sense vertical direction and loss of balance is produced by the inner ear. It is possible that there was an effect on the normal functioning of the inner ear while the subject performed the usual body movements in the somewhat unusual position or attitude. Since this reclining attitude is a natural one for resting and sleeping, it is unusual only from the standpoint of the subject's being called on to perform various tasks. It is doubtful that this possible ear effect is a serious consideration; however, inasmuch as all subjects reported their condition as very confortable with no sense of dizziness, a factor which usually accompanies the disruption of normal functioning of the inner ear. Furthermore, several subjects reported a sensation of being inclined for several seconds after leaving the test device; this feeling indicated that the subjects' sensory systems had actually become adjusted to the inclined attitude.

Another possible factor responsible for the poor judgment of the vertical attitude is the lack of suitable visual cues. The tests were conducted near the middle of a large hangar with the test subjects standing on a rather small 4- by 16-foot walkway. Aside from this walkway, there were only a few distance portions of the building structure with which the subject could obtain visual cues of the local vertical or direction of the simulated gravity field. It is very likely that use of a much larger walkway and some posts or vertical reference marks mounted on the walkway would provide the subjects with a more natural visual reference and minimize some of the effects noted.

Walking and Running

Although the 16-foot-long runway proved to be inadequate for these tests, it was possible for the test subjects to note some qualitative effects. It was not possible to reach maximum speeds because of the shortness of the walkway; however, the subjects could walk and run to some extent, but they experienced difficulty in trying to accelerate to a walking or running pace and in stopping in a normal manner. The low foot traction caused the feet to slip unless care was taken to accelerate and decelerate slowly. The sensation of walking or running can be compared somewhat with that of trying to run or walk on ice or a highly polished floor. The use of footwear with some form of high-friction-producing sole material would undoubtedly overcome this problem to some extent but was not included in this exploratory study.

These observations compare qualitatively with those presented in references 3 and 4, in which test subjects attempted to walk with magnetic-type shoes in a condition of weightlessness and also to walk with conventional shoes under approximate lunar-gravity conditions in an airplane flying a Keplerian trajectory. One of the persons who participated in the subject tests of this report had the opportunity to fly in one of the airplanes, a C-131B, engaged in these Keplerian flights, and he reported sensations and reactions similar to those experienced using the newly developed technique.

The problem of low foot traction should be recognized as a safety hazard to the lunar explorer inasmuch as it causes difficulty for the explorer to shift his position rapidly to avoid being struck by moving or falling objects or to gain a surer foothold or handhold while in a precarious position.

Vertical Jumping

Measurements were made to determine the maximum vertical heights to which the test subjects could jump under the influence of both the earth gravity and the simulated lunar gravity. During these tests, accelerometers were strapped to the subject to record the vertical accelerations generated by each subject who was asked to perform a series of jumps of increasing heights up to those obtained by maximum exertion. A movable target set at various given heights above normal-standing eye level was used as a height reference, and the subject jumped to bring the target to eye level. These tests provided a qualitative indication of the subject's ability to judge and control his jump.

For the tests of jumping in the earth gravity or in a condition of 1 g, average maximum heights from 20 to 22 inches were obtained. To achieve these heights the subjects generally jumped from a crouched position, giving a propelling stroke (that is, the vertical movement of the upper part of the body prior to the time the feet leave the floor) of about 12 inches.

Average maximum jumping heights from 8 to 9 feet were obtained for the lunar gravity or the condition of 1/6g, as produced by the equipment. Application of height corrections to account for the gravity gradient produced by the test equipment, as outlined in appendix B, showed that heights from 12 to 14 feet could be achieved under a condition of constant lunar gravity. The subjects were observed to crouch all the way to their heels, a distance of about 24 inches, in their attempts to achieve these maximum heights. Furthermore, during the initial crouching motion, the subject's feet were often observed to lift up momentarily from the surface; this action indicated that the subject was actually pulling his feet upward toward him in an attempt to build up a greater springing action. The subjects commented that the timing or coordination of the jumping motions was difficult and required considerable concentration in order to achieve the maximum heights.

The results of the acceleration measurements are presented in figure 11, where the incremental peak accelerations generated during the initial jumping motion are plotted as a function of the percent of maximum jump height for the different subjects and the two gravity levels. This figure reveals that although the capability of the subjects, as indicated by this incremental peak acceleration, varied, there was a consistent reduction from 50 to 70 percent in the performance of each subject produced by lowering the gravity. Studies to determine the reasons for this reduction were considered to be beyond the scope of this report.

For the lunar-gravity condition, the test subjects experienced considerable difficulty in maintaining their balance or proper attitude during the jump after leaving the surface. This loss of balance was apparently due to the previously mentioned difficulty in judging the vertical direction and also to a problem of minimizing their angular momentum prior to loss of foot contact with the surface of the walkway. In the normal earth gravity, the problem with angular momentum is not encountered because of the short duration of the jump, approximately 0.5 second. For the lunar-gravity condition, however, the maximum height provided periods up to about 4 seconds which were sufficient to permit small residual angular velocities to produce fairly large angular displacements of the body at the moment of contact with the surface.

The test subjects experienced some difficulty in judging their jumps and controlling their jump heights accurately for both gravity conditions for heights requiring a minimum expenditure of effort. For the lunar condition, these heights were approximately 2 to 3 feet (equivalent to 4 to 6 inches for the earth condition). This result suggests the possibility that if standard 8- to 10-foot ceilings are used in the lunar base housing, 6-foot-tall explorers may have trouble with bumping their heads on the ceiling while performing mild activities.

Falling

Although there were a number of occasions when the subjects lost their balance during the vertical jumps for the lunar condition and fell distances equivalent to 12 to 14 feet in various uncontrolled attitudes, there were no instances where the subjects sustained any injury. Because of the relatively long duration of the fall, it was a relatively simple matter to extend the arms or legs properly to absorb the landing impact even when landing on the back. The landing velocities from these maximum jumping heights were approximately 11 to 12 feet per second and of the same order of magnitude as the velocities developed under the earth gravity. Flat-on-the-face falls from a standing attitude under the influence of the lunar gravity were very gentle and could be tolerated even without any breaking effort by the arms or legs.

While no tests were made specifically for the earth-gravity condition, experience has shown that serious injuries can result from falls from heights considerably less than the maximum jumping heights from 20 to 22 inches and even from a normal standing attitude.

Gymnastic Feats

Under the influence of the lunar gravity, the test subjects could easily perform a number of gymnastic feats that under normal earth conditions would be attempted only by a skilled and practiced gymnast. These feats included, in addition to the previously discussed high jumps, forward and backward flips, handstands, and headstands. Perhaps the effects of the lunar gravity on a person's physical capabilities could be described as exhilarating because of the increased ability to perform all sorts of movements without penalty of bodily harm.

Climbing Stairs, Ladders, and Poles

Simple tests which consisted of walking up a set of five steps to a landing revealed that although there was no serious problem in climbing the stairs under the condition of lunar gravity, it was far simpler and required less energy and concentration merely to jump from the walkway surface to the landing, a vertical distance of about 4 feet. The particular test setup did not lend itself to the condition of walking down the stairs forward. However, it was a very simple matter to come down from the landing merely by jumping off backwards; this action suggested that the test subjects should have found it equally simple to jump down rather than use the individual steps. These results, of course, are not particularly surprising inasmuch as the vertical distance of 4 feet is the equivalent of a distance of only 8 inches under earth-gravity conditions.

These results suggest the possibility that the normally accepted riser-and-tread dimensions for stairways should be altered for use in the design of lunar base housing. More extensive studies will be required to establish the suitable dimensions.

In the tests of a subject's climbing a ladder in the lunar-gravity condition, it was found that use of the feet required a rather slow and deliberate pace in order to keep the feet properly placed on the ladder rungs. It was far simpler to merely grasp the rungs with the hands and let the feet dangle unused. The strength of the arms was adequate for lifting the weight of the body. It is very likely that if the subject were carrying an appreciable load of, say, 50 lunar pounds on his back, he would have found it necessary to use the feet because of inadequate strength in the arms.

The task of climbing a pole was likewise relatively simple for the test subjects using only the hands and arms. As a matter of fact, it was even possible to use only one hand for climbing. Under the earth-gravity condition, the same subjects found it a very difficult task to climb the pole even with the use of the legs to grip the pole in the normal climbing fashion.

These tests were carried out using the 40-foot suspension cable and the gravity gradient for this cable length was found to be noticeable. It is suggested, therefore, that for tests of this nature a cable length of at least 80 feet would be desirable to minimize the change in gravity level as the subject progresses up or down the stairs or other devices.

APPLICATION OF THE GRAVITY SIMULATOR TO VARIOUS STUDIES

A number of future applications for use of the lunar-gravity simulator have already been discussed or implied in the preceding sections. These and other applications are summarized as follows:

(1) Evaluation of the various forms of man's self-locomotion, including the range and duration limits of man's walking and running on the lunar surface and carrying various amounts of equipment or loads.

(2) Evaluation and development of auxiliary devices such as rocket-powered jump packs, gyrostabilizers, and manpowered vehicles to augment or extend the man's capabilities.

(3) Design and development of practical spacesuits for lunar exploration.

(4) Design and development of lunar base housing and space-station features.

(5) Familiarizing lunar-mission personnel with their capabilities and sensations while under the influence of the lunar gravity.

A special adaptation of the subject technique for use in studies carried out as part of item (1), as just listed, is illustrated in figure 12. For these studies it is desirable to have a walkway of essentially unlimited length in order to determine the practical distances that the explorers encumbered with their spacesuits and equipment will be able to cover while exploring the lunar surface. The unlimited length is achieved by using a circular walkway, the radius of which is equal to the walkway displacement h_w, as given in figure 8 for a given cable length. It is desirable to use a relatively long cable so that the radius of the walkway will be large and, consequently, the curvature, small. It is estimated that a radius of at least 20 feet would minimize problems that might be encountered in trying to walk or run on the curved surface, and it is believed that the curvature would have negligible effects on the results for this type of study. Even though a walkway of this size would require a rather long cable of about 120 feet, this adaptation has the advantage of eliminating the need for the overhead track-and-trolley system that must otherwise be used and must be kept alined with the test subject at all times.

In order that measurable and meaningful results from studies that will be universally useful for these various applications be obtained, it appears to be very desirable to establish standardized testing procedures utilizing clearly defined tasks that are representative of the various modes of self-locomotion discussed previously. A few suggested tasks are presented in table I to illustrate the type of procedures. A complete definition of these tasks is considered to be beyond the scope of this report.

Inasmuch as many of the tests to be undertaken by a number of different persons will depend on the subjective evaluation of a particular set of conditions, it is desirable to use a standard rating system that applies a quantitative value to a qualitative rating in order to simplify the processing and presentation of the test data. A suggested system to be used for this rating procedure is presented in table II. A number system is suggested where effects can be separated into clearly defined categories and it is desirable to show more numerous graduations.

CONCLUDING REMARKS

Consideration has been given to adapting different techniques utilized in weightlessness studies to the needs for simulating lunar gravity for studies of the self-locomotive capabilities of man in the lunar environment, but these techniques have been found to be inadequate. Consequently, a new technique has been devised, and on the basis of the work completed to evaluate this new gravity-simulation technique, the following comments are made.

The inclined-plane technique utilizing simple and inexpensive cable-suspension equipment appears to be a practical and useful method for the subject studies, particularly, since the technique can provide essentially unlimited duration of the testing period and adequate space for performing all modes of locomotion.

Although the Keplerian trajectory technique has a number of shortcomings, it would appear desirable to use this method as a means of cross-checking or correlating some of the significant results of tests made using the gravity-simulation technique for some types of locomotion studies.

The lunar explorers should be able to walk and run on the moon, but they will experience difficulty in changing their position rapidly as might be required in avoiding a falling object. They should be able to jump vertical distances up to 12 or 14 feet on the moon when unencumbered with a spacesuit or other equipment but will experience difficulty in maintaining their balance. However, falls from these heights under similar conditions are not likely to result in personal injury.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 14, 1963.

APPENDIX A

CALCULATIONS FOR THE DESIGN CHARACTERISTICS OF THE CABLE-SUSPENSION GRAVITY SIMULATOR

It is evident from the diagram presented in figure 13, that the inclination angle θ between the suspension cable and the vertical required to produce a given simulated gravity acting on the test subject standing on the walkway is given by the following equation:

$$G = g \sin \theta$$

or

$$\theta = \sin^{-1}\left(\frac{G}{g}\right) = \sin^{-1} N \tag{A1}$$

where N is the ratio of the desired simulated gravity G to the earth gravity g. The displacement of the walkway h_W, measured parallel to the floor and required to produce the necessary θ, is given by the following equation:

$$h_W = L \sin \theta - h \cos \theta \tag{A2}$$

where L is the suspension-cable length taken from the upper cable attachment point to the test subject's center of gravity and h is the distance between the subject's center of gravity and the soles of his feet. For purposes of this report, the value of h is assumed to be equal to 3.5 feet. Combining equations (A1) and (A2) gives the equation for h in terms of N:

$$h_W = LN - h \cos\left(\sin^{-1} N\right) \tag{A3}$$

Curves showing the variations of θ and h_W with the gravity ratio N, as expressed by these equations, are presented in the left-hand portion of figure 8.

From figure 13 the gravity component G acting on the subject is seen to increase by an amount ΔG as the subject is displaced from the walkway by an amount Δh during a jump or while climbing steps; this increase is due to the change in inclination angle $\Delta\theta$ according to the following relationship:

$$G + \Delta G = g \sin(\theta + \Delta\theta) \tag{A4}$$

where the value of $\Delta\theta$ is found as follows:

$$\sin \Delta\theta = \frac{\Delta h}{L}$$

or

$$\Delta\theta = \sin^{-1}\left(\frac{\Delta h}{L}\right) \tag{A5}$$

The value of ΔG is obtained by subtracting equation (A1) from equation (A5):

$$\Delta G = g\left[\sin(\theta + \Delta\theta) - \sin \theta\right]$$

or

$$\Delta G = g(\sin \theta \cos \Delta\theta + \sin \Delta\theta \cos \theta - \sin \theta) \tag{A6}$$

If it is assumed that $\Delta\theta$ is small, then $\cos \Delta\theta \approx 1$, and equations (A5) and (A6) can be combined and simplified to yield the following:

$$\Delta G = g\frac{\Delta h}{L} \cos \theta$$

or

$$\frac{\Delta N}{\Delta h} = \frac{\cos \theta}{L} \tag{A7}$$

where $\Delta N = \frac{\Delta G}{g}$. Curves showing the variation of the gravity-gradient factor $\frac{\Delta N}{\Delta h}$ with cable length L for different values of the gravity ratio N are given in the right-hand side of figure 8.

APPENDIX B

DETERMINATION OF THE GRAVITY-GRADIENT CORRECTIONS FOR JUMPING HEIGHTS

Inasmuch as the cable-suspension system produces an increase in the simulated gravity as the height of the subject above the walkway is increased, it is necessary to apply corrections to the measured jumping heights obtained by test subjects in order to determine the heights that would be obtained under conditions of constant acceleration. The velocity V of the subject's body as his feet break contact with the surface of the walkway can be calculated by either of the following equations:

$$V = \sqrt{2G\,\Delta h_{corr}} \qquad \text{(B1)}$$

or

$$V = \sqrt{2G_{av}\,\Delta h} \qquad \text{(B2)}$$

where Δh_{corr} is the height that would be achieved with a constant gravity and Δh is the height that was measured for the variable gravity which had an average value G_{av}. The value of G_{av} for the cable-suspension system is expressed as follows:

$$G_{av} = G + \frac{\Delta h}{2}\left(\frac{\Delta N}{\Delta h}\right)g \qquad \text{(B3)}$$

Consequently, equating equations (B1) and (B2) and using equation (B3) for the value of G_{av} yields the following expression for the corrected height:

$$\Delta h_{corr} = \Delta h\left[1 + \frac{\Delta h}{2N}\left(\frac{\Delta N}{\Delta h}\right)\right] \qquad \text{(B4)}$$

In the case of the jumping tests made with the preliminary setup shown in figure 9, the cable length was approximately 60 feet and the gravity ratio was about 0.17. The corresponding gravity-gradient factor was about 0.017 which, for a typical maximum measured height of 8.5 feet, yields the following solution to equation (B4):

$$\Delta h_{corr} = 8.5\left[1 + \frac{8.5(0.017)}{2(0.17)}\right] = 8.5(1.43) = 12.2 \text{ feet}$$

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3. Loret, Benjamin J.: Optimization of Manned Orbital Satellite Vehicle Design With Respect to Artificial Gravity. ASD Tech. Rep. 61-688, U.S. Air Force, Dec. 1961.

4. Simons, John C.: Walking Under Zero-Gravity Conditions. WADC Tech. Note 59-327, U.S. Air Force, Oct. 1959.

TABLE I.- SUGGESTED TASKS FOR EVALUATION OF MAN'S SELF-LOCOMOTIVE CAPABILITIES

Task	Description	Measurements	Variables
Walking	Walk steadily at various speeds up to maximum	Variation of pulse or respiration rate with time Maximum walking distance	Gravity ratio from 1 to 0 Test subject Loads Shoes and clothing Spacesuit parameters, including suit pressure
Running	Run steadily at various speeds up to maximum	Variation of pulse or respiration rate with time Maximum running distance	
Jumping	Jump vertically various heights up to maximum Jump horizontally various heights up to maximum	Body accelerations Maximum distances	
Climbing slopes	Climb inclined walkway with various slopes	Time to climb given distance Maximum slope	

TABLE II.- SUGGESTED RATING SYSTEM

[For use in subjective tests of the ability of various test subjects to perform specific tasks]

Rating	Definition
0	No effort
1 2 3	Easy
4 5 6	Moderately easy
7 8 9	Difficult
10	Impossible

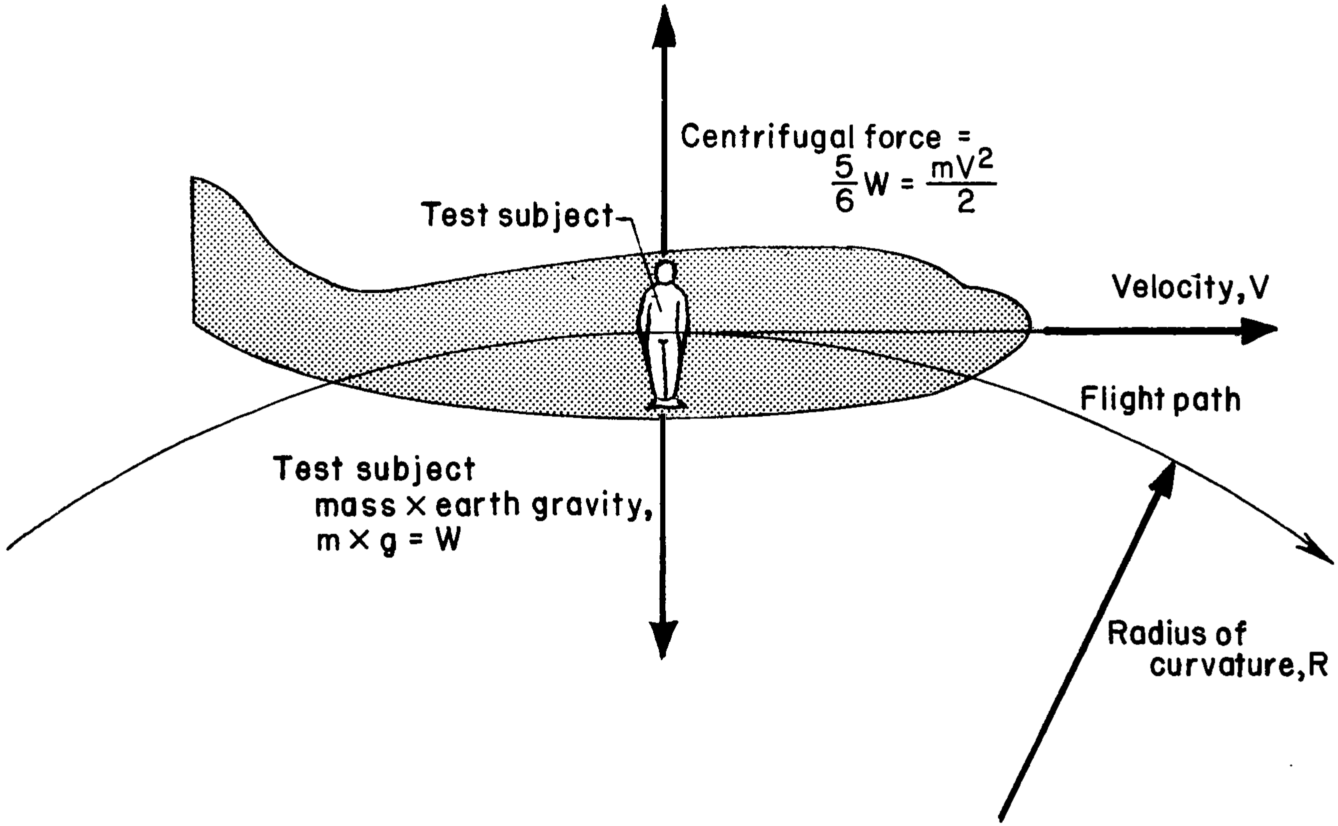


Figure 1.- Illustration of forces acting on test subject at peak of a near-Keplerian trajectory to produce lunar-gravity condition.

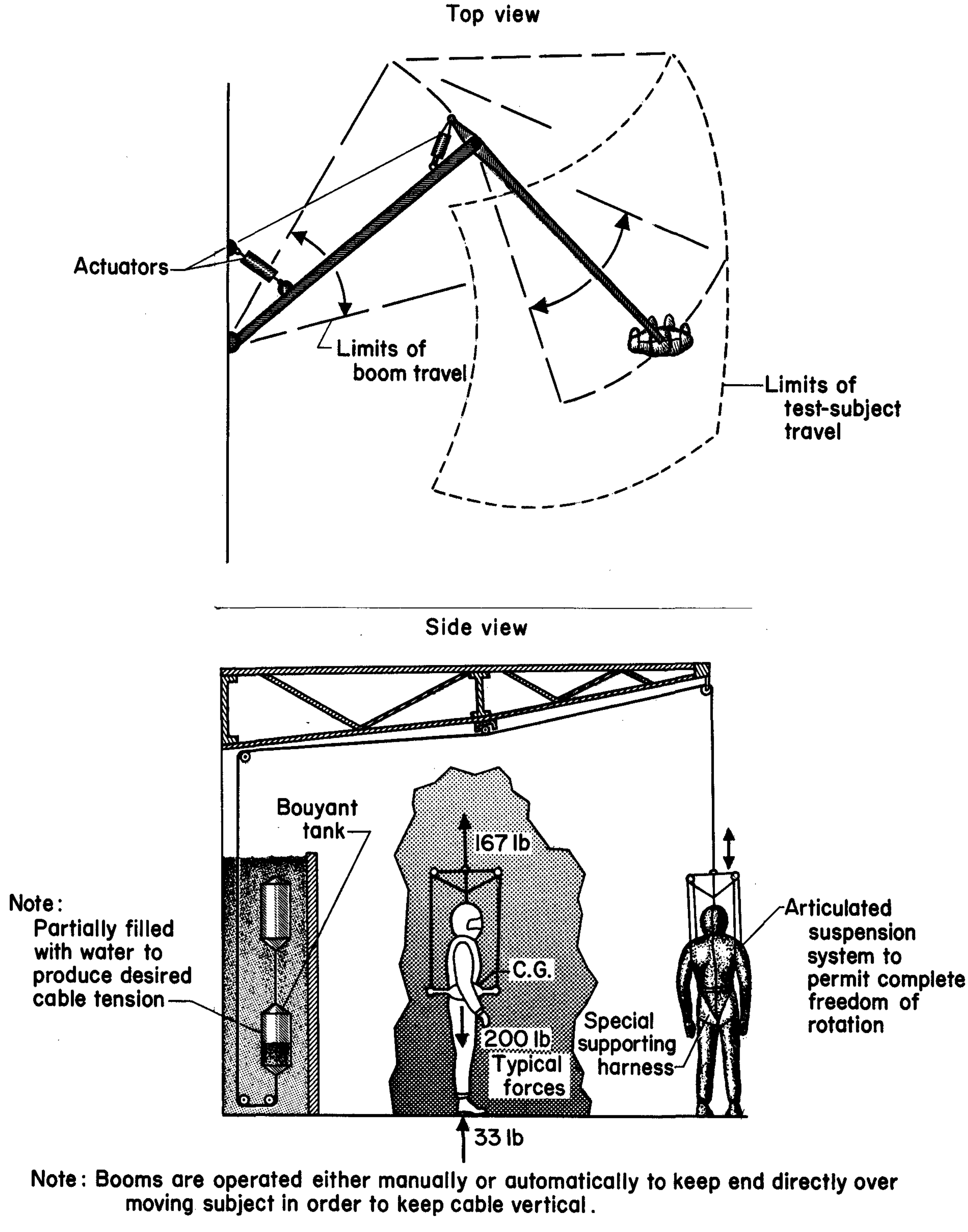


Figure 2.- Illustration of a vertical-cable-suspension scheme to produce lunar-gravity conditions.

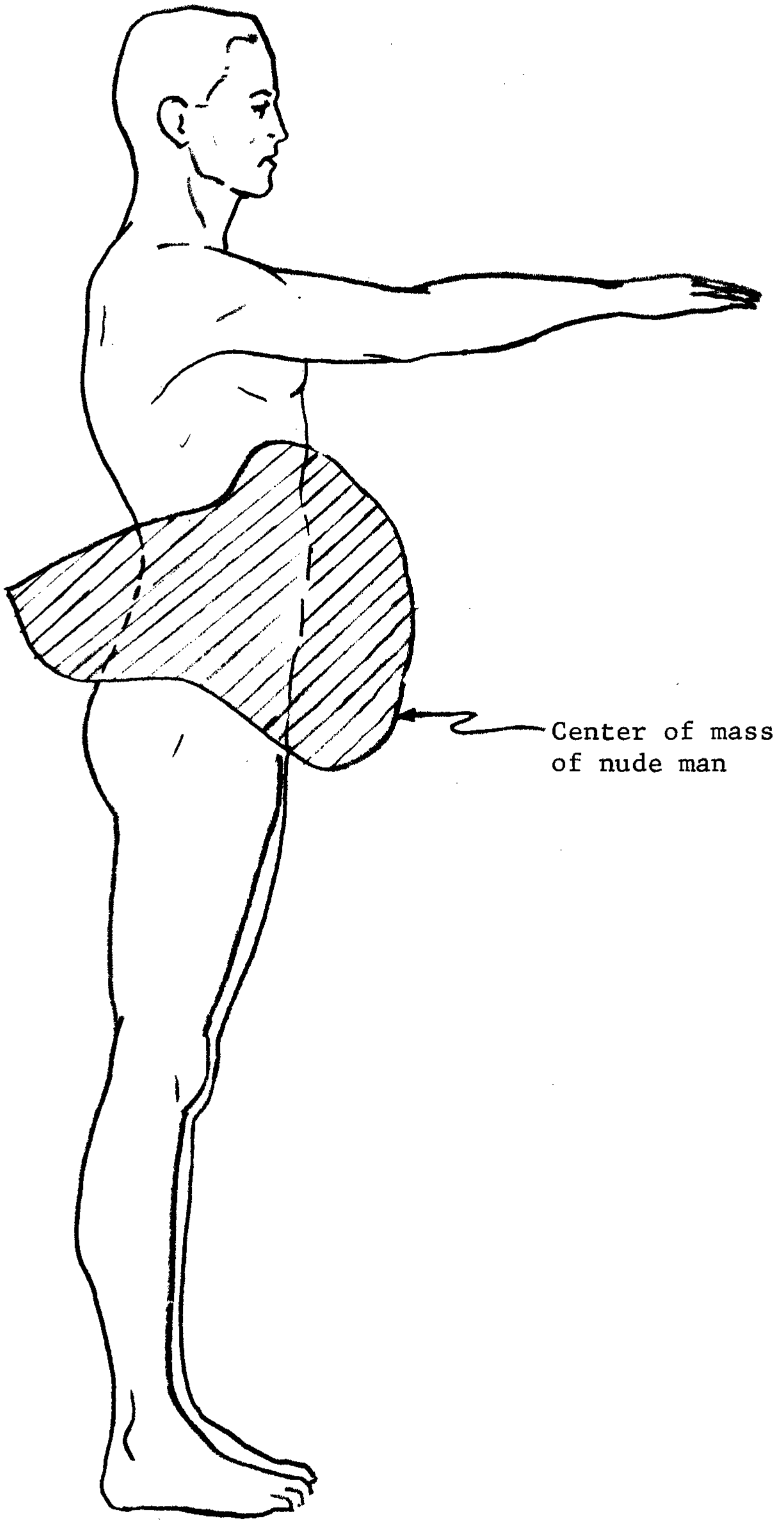


Figure 3.- Sketch showing the loci of man's center of gravity for all possible body movements.

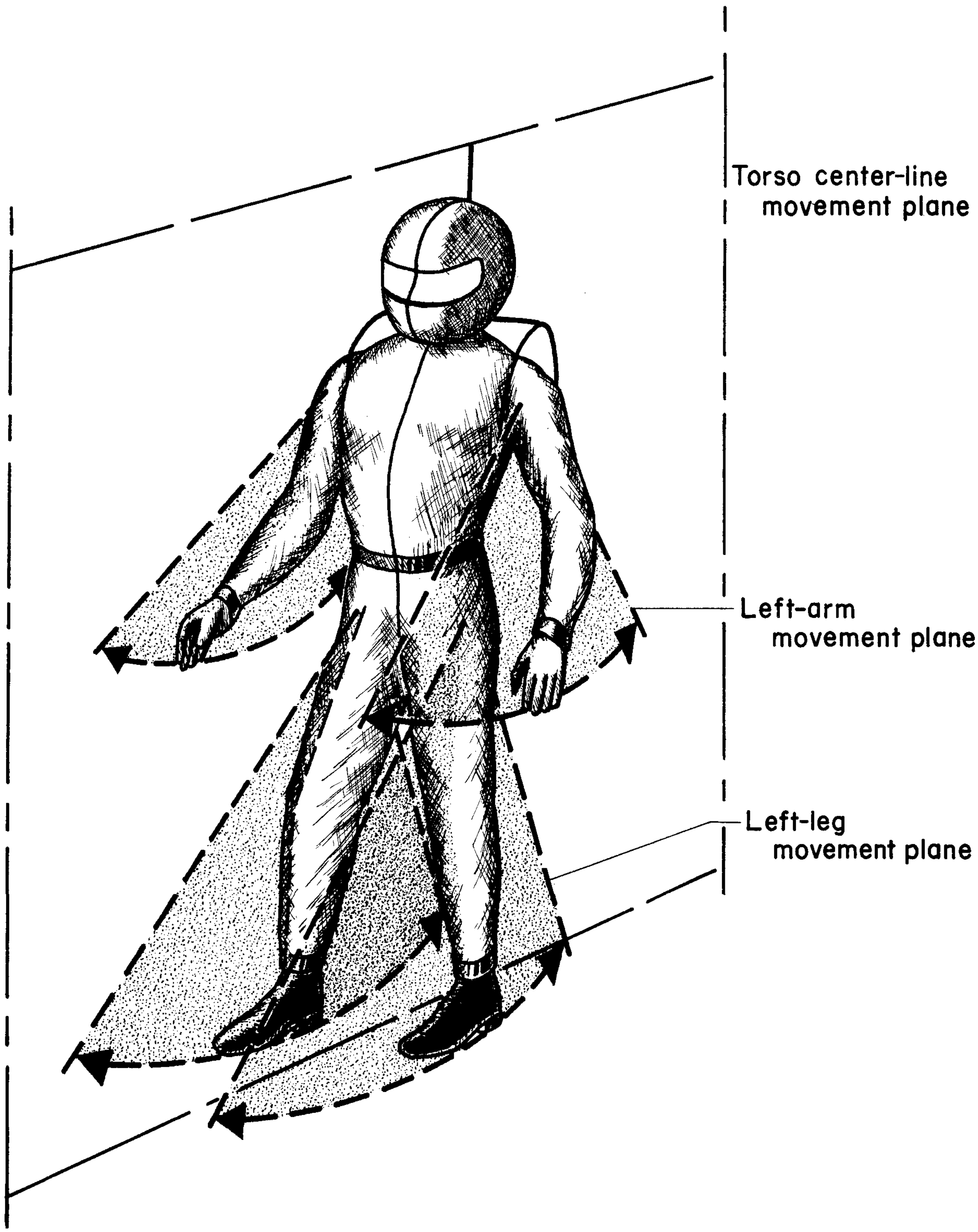


Figure 4.- Sketch illustrating coplanar movement of body members during walking, running, and jumping.

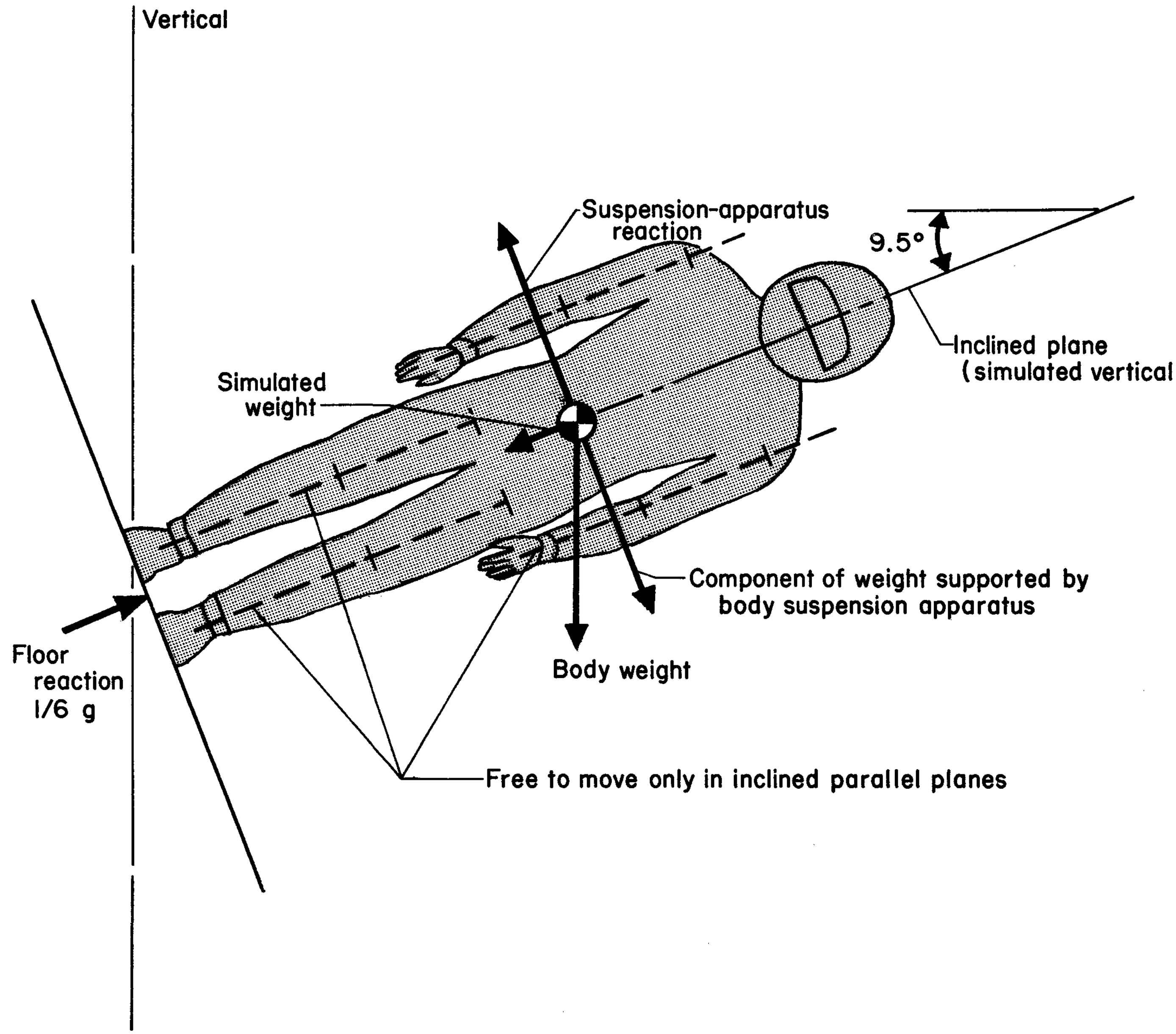
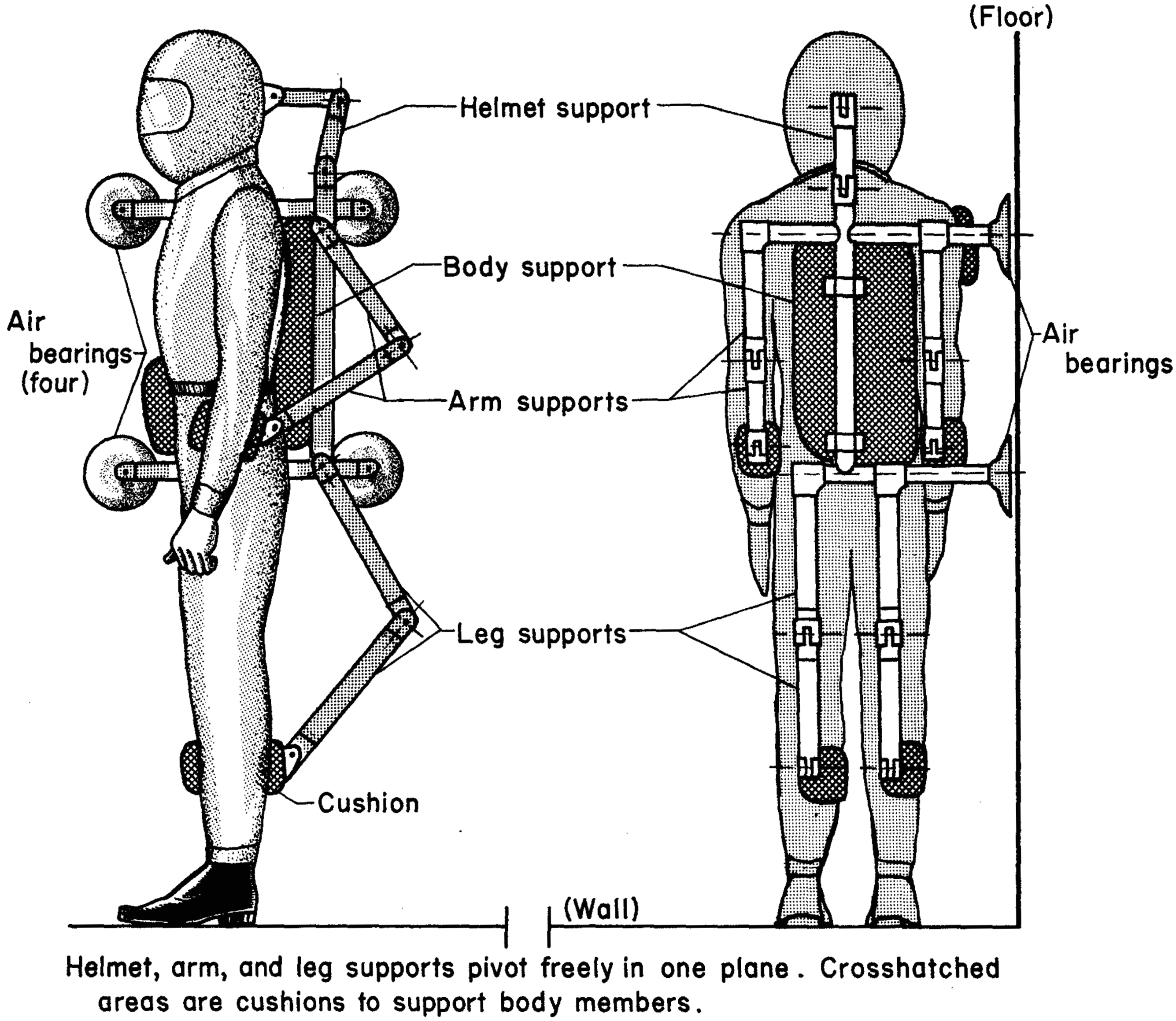
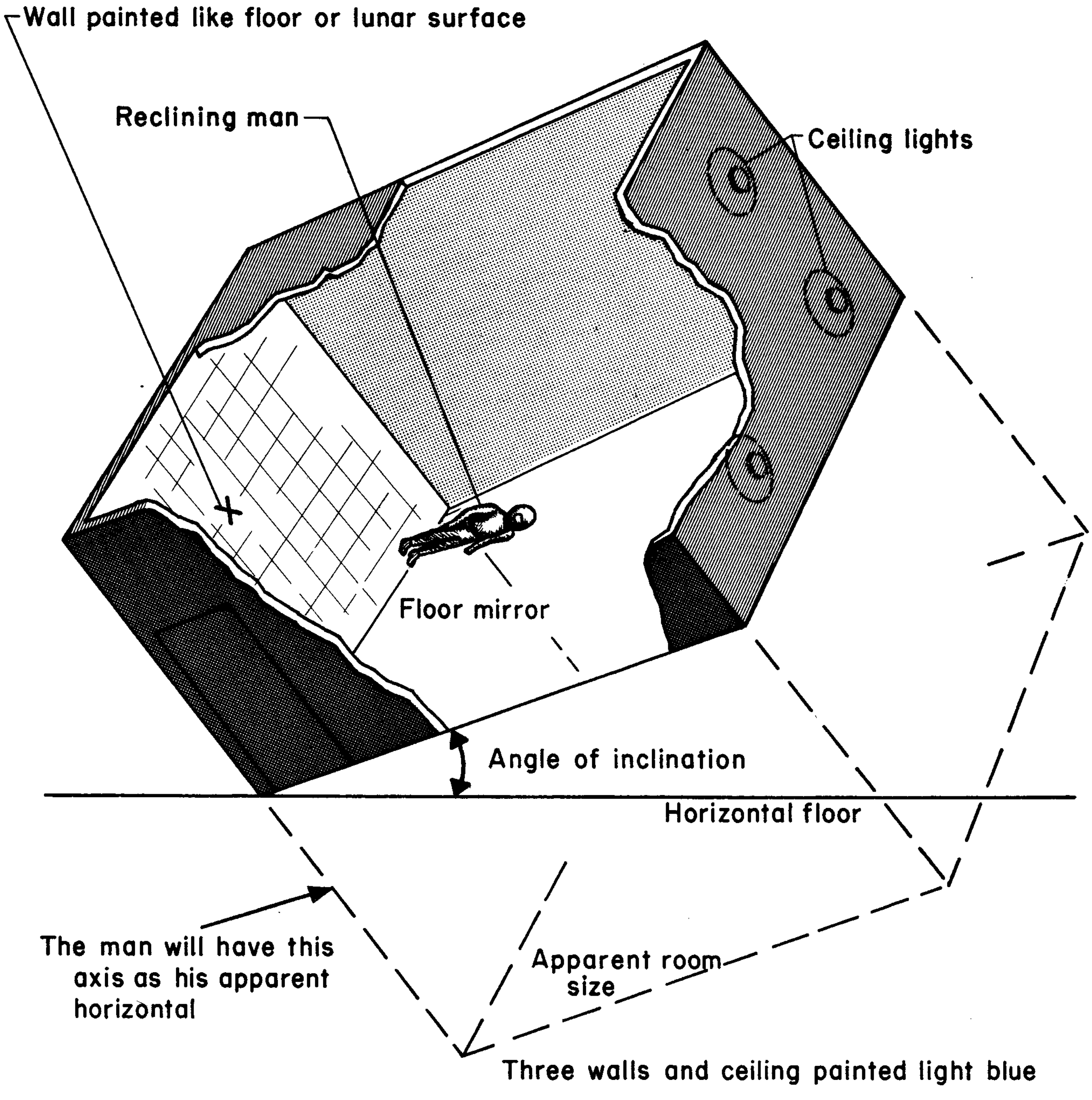


Figure 5.- Sketch illustrating principle of inclined-plane technique for lunar-gravity simulation.



(a) Body-support frame.

Figure 6.- Sketches of a preliminary design for a lunar-gravity simulator based on inclined-plane technique.



(b) Inclined room.

Figure 6.- Concluded.

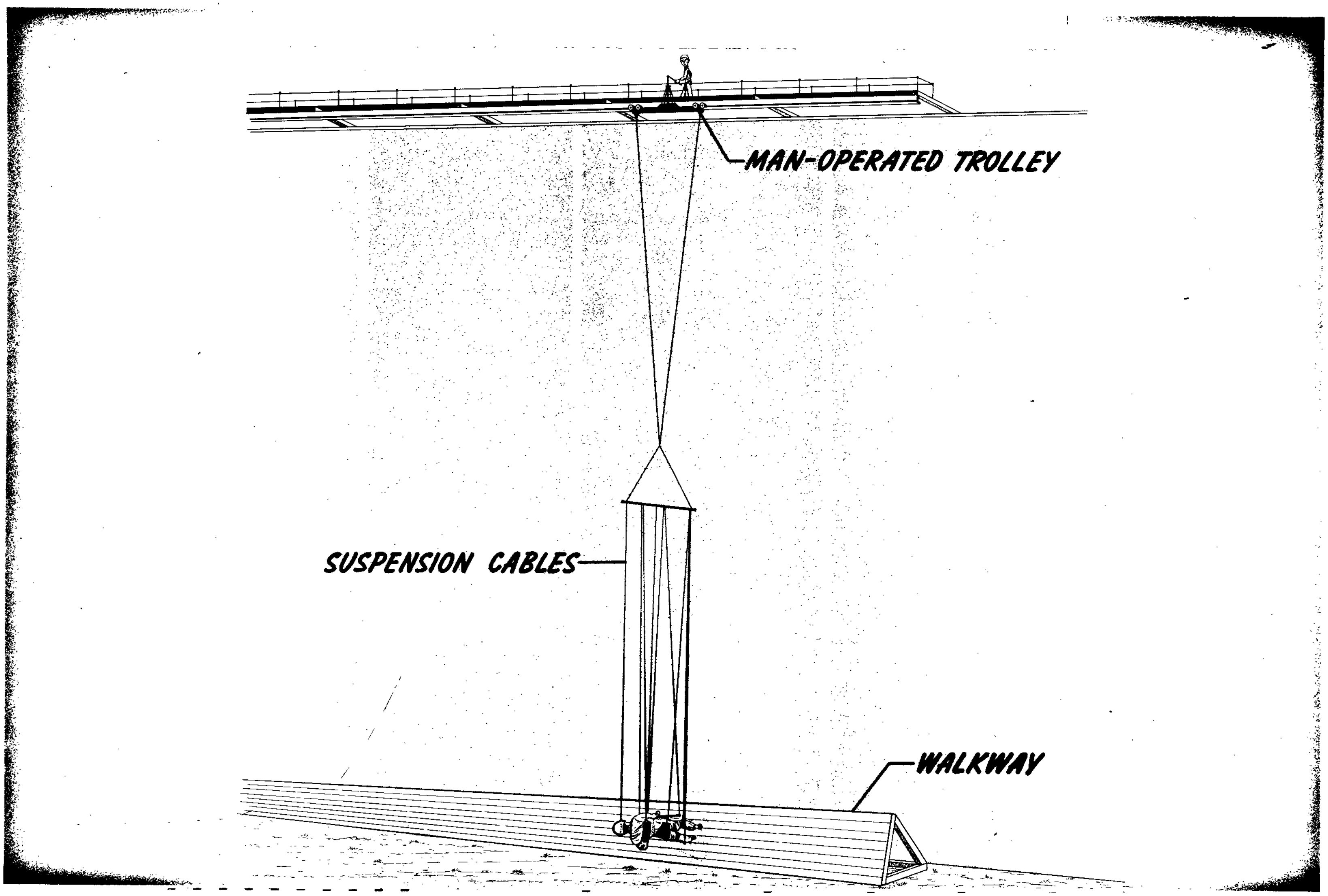


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Figure 7.- Sketch of cable-suspension system applied to proposed inclined-plane technique for simulation of lunar gravity.

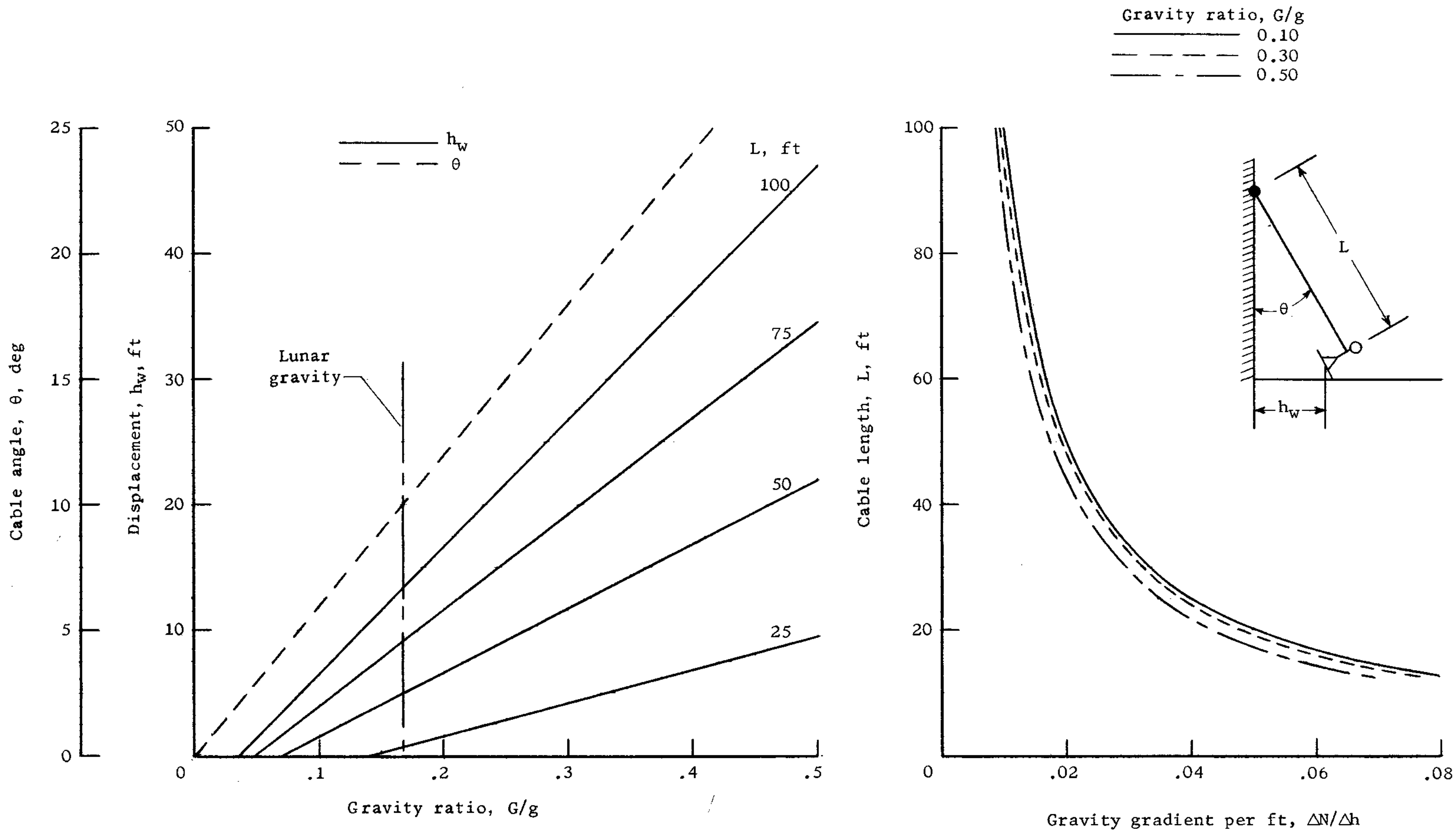

Figure 8.- Required walkway displacement h_w and cable inclination angle θ with gravity ratio and variation of gravity gradient with suspension-cable length for lunar-gravity simulator.

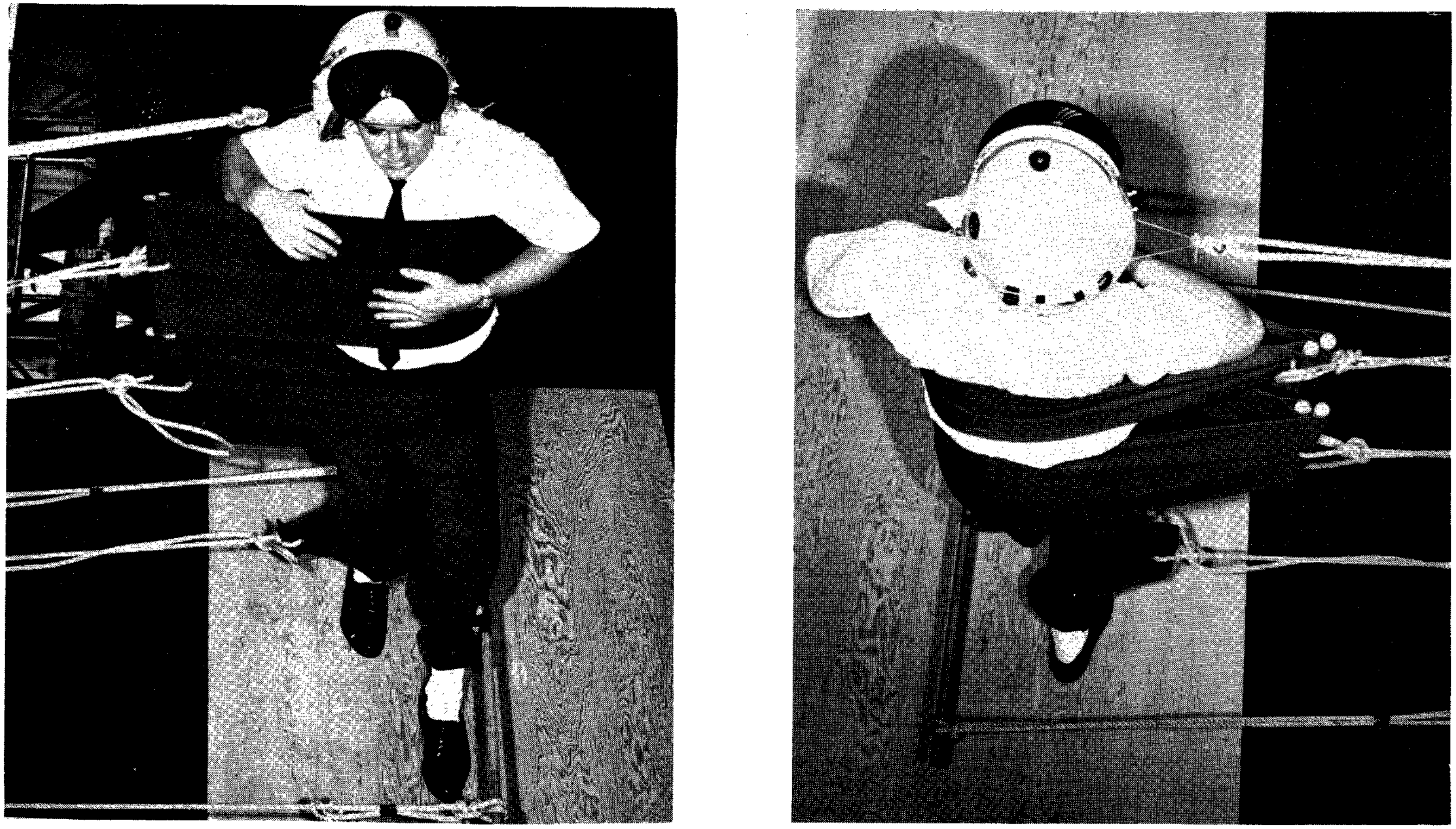

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Figure 9.- Photograph of preliminary setup of lunar-gravity simulator used to evaluate proper points for suspension of body members.

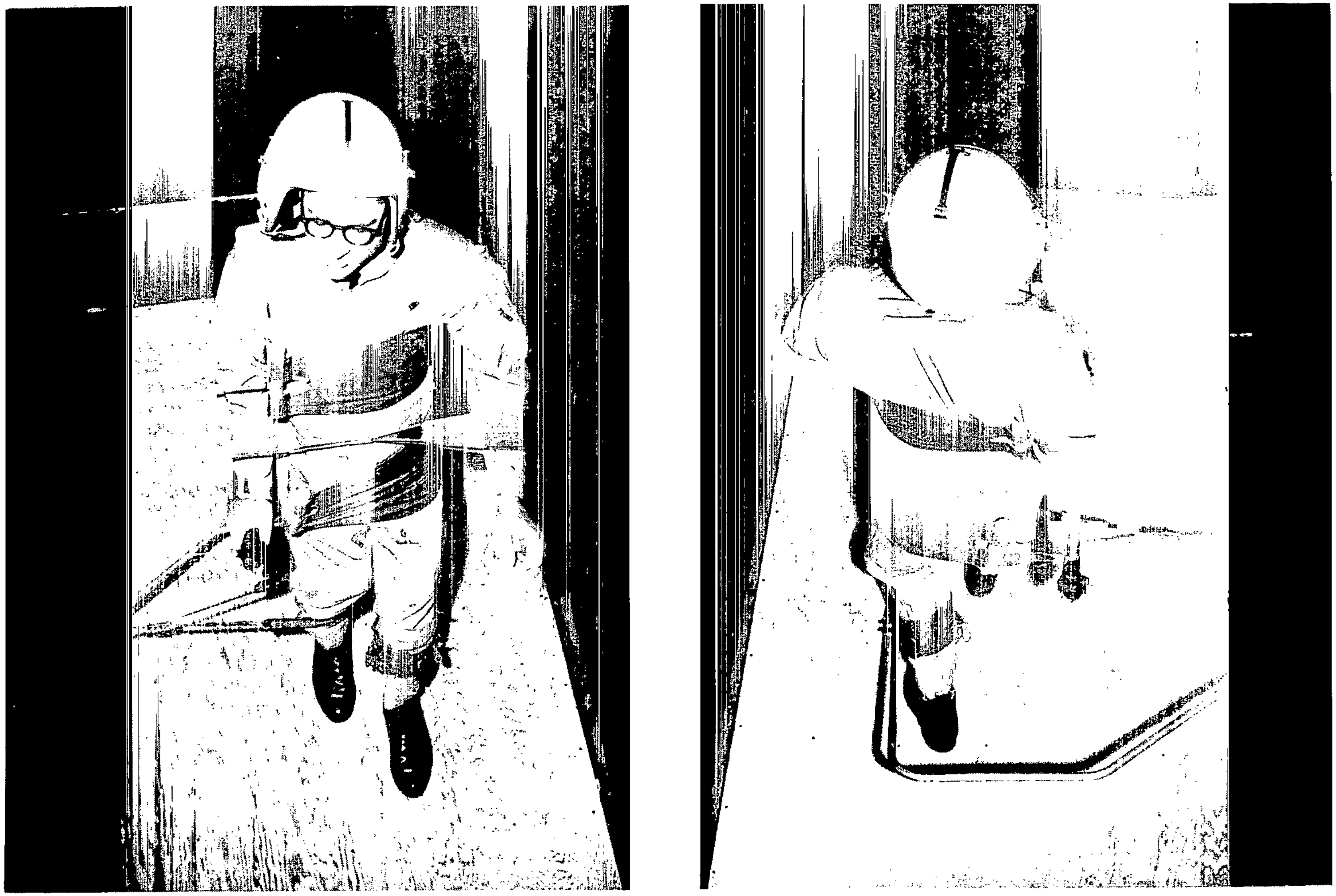

Figure 10.- Photographs of refined setup of lunar-gravity simulator. L-63-7515

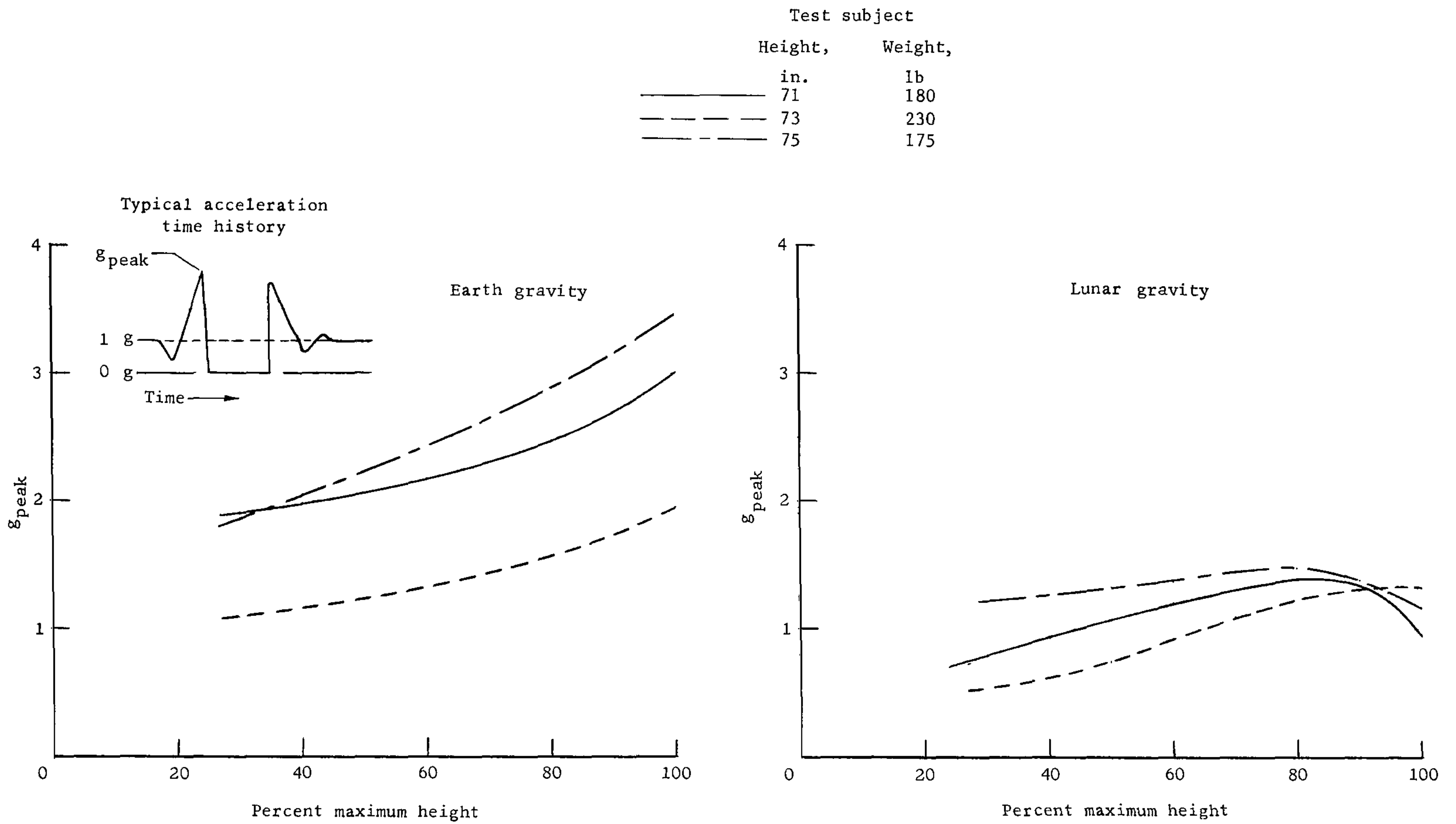

Figure 11.- Variation of peak acceleration generated by three different test subjects performing vertical jumps under influence of earth gravity and simulated lunar gravity.

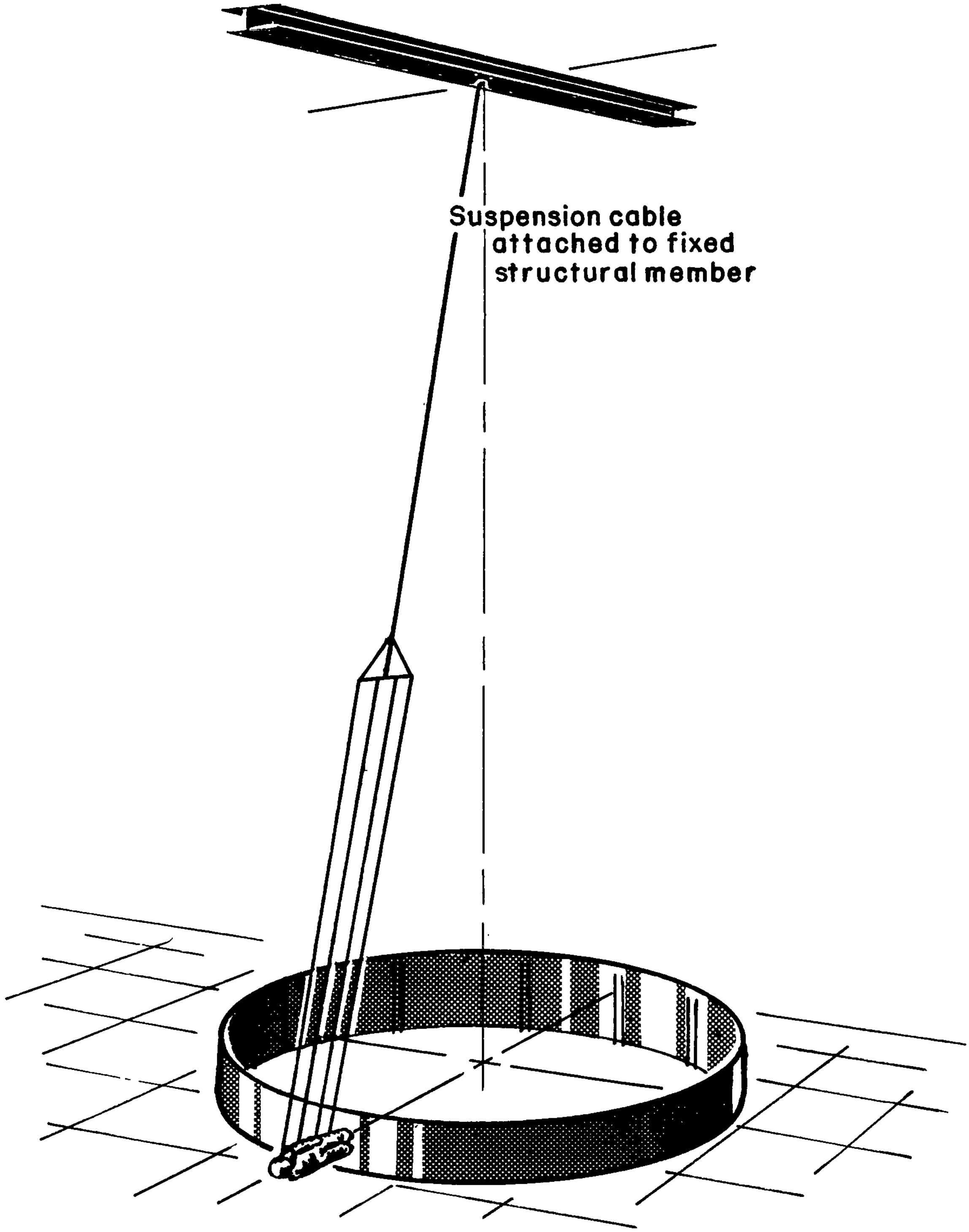

Figure 12.- Sketch of proposed circular walkway for studies of walking and running endurance.